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The Estimated Merger Rates of GW150914-like Binary Black Holes from the Astrophysical Argument Perspective and Their Implications

by

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Abstract

In this paper, we looked at the three possible formation paths for GW150914-like BBH mergers. They are the chemically homogenously evolution(CHE), isolated binaries(IB) scenario, and the dense stellar environment(DSE) scenario. These three models predict consistent merger rates with the inferred merger rate of 2-400 Gpc^{-3} yr^{-1} [1] from the detection of GW150914. Although a definite conclusion cannot be drawn on which scenario corresponds to GW150914-like mergers, we found that the IB scenario and CHE scenario are more probable over the DSE scenario. We noticed that strong spin alignment can possibly distinguish isolated binaries scenario from the dense stellar environment scenario, and with both IB and CHE scenario favouring aligned spins, the BBHs formed from CHE scenario mostly merge in $z < 1.5$ [2], while that of IB can occur at high red-shift. Further studies on comparison between the two conventional models (IB and DES) and CHE model is needed in order to constrain and identify features that can better distinguish the three models.

Introduction

Around 100 years after prediction of Einstein's general theory of relativity, the first gravitational wave was recorded on September 14^{th}, 2015 from a binary black holes merger by LIGO. This observation does not only confirm the existence of gravitational wave, but also the existence of binary black hole systems and large stellar masses black holes. One of the naturally raised questions of any astronomical observations is that how often we will be able to see such kind of signal, i.e. the detection rate. For practical purpose, predicting a detection rate is important in the sense that observatories know what to look for, and have the right setting for the anticipated detections. For knowledge, in general, checking the consistency between rates calculated and their underlying assumptions from theoretical models with the actual detections can help scientist to modify the models, and indirectly gain information of which models have a higher probability of resembling the actual scenario.

This present paper provides a summary of the three possible aspect of formation paths for GW150914-like events, which are identified by their consistent predicted merger rates with the rate inferred from the actual observation. We aim to provide a better understanding on what factors could affect the merger rates, and also observational features that could distinguish formation models of GW150914-like BBHs from one another. In Section 1, we will go through the detection of GW150914 and its inferred BBH merger rates. In Section 2, we discussed the three formation paths and their prediction on merger rates of GW150914-like BBHs. From that, we discuss the important factors and assumptions behind those models, and the implications we can made when comparing the three formation paths. Lastly, suggested future studies and expected cooperation between LIGO and other observatory are mentioned in Section 3.

1. Background: The Detection of GW150914

1.1 LIGO's Targets and Expectations before the Detection of GW150914

Among all the plausible astrophysical sources of gravitational waves, binary neutron stars'(BNS) mergers have been considered to be the most promising candidates over the years. Several BNS systems had been observed and known to be within 1 Gyr of merger [3]. While there are theories suggesting ways of formations of binary black holes(BBH), there was no supporting evidence before the detection of GW150914.

With the main target being BNS mergers, LIGO's observation is set at what is known to be a "high frequency window" --- with targeted gravitational waves oscillation frequencies range from 10Hz to 1000 Hz. Its most sensitive band lies between 100-300 Hz [4].

While BBH systems are also taken into consideration in many papers regarding LIGO possible detections, it was not expected to have a final total mass larger than 30 $M_{\odot}$. This is based on astrophysical consideration of how stellar mass black holes(BH) can be formed, and also on the fact that BBH with total mass around 30 $M_{\odot}$ gives a merger frequency of 600 Hz. Larger masses systems shift toward lower frequencies and so spend less time in the LIGO passband. Thus, a large portion of wave signals generated before the typical ring down of merging BBH systems will not be analysable and will be undistinguishable from noise.

1.2 Predictions and Assumptions on Detection Rate Adapted before GW150914

IFO	Source[a]	$N_{\rm low}$ $\rm yr^{-1}$	$N_{\rm re}$ $\rm yr^{-1}$	$N_{\rm high}$ $\rm yr^{-1}$	$N_{\rm max}$ $\rm yr^{-1}$
Initial	NS-NS	2×10^{-4}	0.02	0.2	0.6
	NS-BH	7×10^{-5}	0.004	0.1	
	BH-BH	2×10^{-4}	0.007	0.5	
	IMRI into IMBH			$< 0.001^b$	0.01^c
	IMBH-IMBH			$10^{-4\,d}$	$10^{-3\,e}$
Advanced	NS-NS	0.4	40	400	1000
	NS-BH	0.2	10	300	
	BH-BH	0.4	20	1000	
	IMRI into IMBH			10^b	300^c
	IMBH-IMBH			0.1^d	1^e

Table 1: Prediction on detection rates of GW150914 [5]

The predicted BBH merger rate adapted by LIGO/Virgo is 0.1-300 $\rm Gpc^{-3}\ yr^{-1}$. Assuming 10 $M_\odot$ for BH mass, optimal horizon distances of 0.161 Gpc / 2.187 Gpc for the Initial / Advanced LIGO, it corresponds to a detection rate of 0.4-1000 $\rm yr^{-1}$ for Advanced LIGO [5].

The rate is drawn from a model of isolated binary-evolution scenario using *StarTrack* and population synthesis [6] with constraints discussed in section IV A in the LIGO prediction paper. Note that the paper exclude rates calculated based on dense stellar environment models in the summary shown in Table 1, as they have relatively large uncertainties, and only limited numbers of models are available makes assigning comparable ranges difficult [5].

1.3 The Rumours about BHBH Merger Detections

On September 25th 2015, Professor Lawrence Krauss started a rumor about a gravitational wave detection at LIGO [7]. While it raised discussion and attentions to the matter, it was believed to be a false signal that LIGO injected on purpose. An update was tweeted by Professor Krauss again on January 11th 2016, claiming that the rumor had been confirmed by independent sources [7]. LIGO spokesperson Gabriela Gonzalez neither confirmed nor denied the rumor, saying that the team was still analysing the data of the run.

1.4 The GW150914 Detection and Its Implications

A gravitational wave signal was reported on September 15, 2015, which was identified as a signal from a binary black hole mergers. Not only did we confirm the existence of gravitational wave, but also the presence of binary black hole with large masses, which was not expected before.

Primary black hole mass	$36^{+5}_{-4} M_\odot$
Secondary black hole mass	$29^{+4}_{-4} M_\odot$
Final black hole mass	$62^{+4}_{-4} M_\odot$
Final black hole spin	$0.67^{+0.05}_{-0.07}$
Luminosity distance	410^{+160}_{-180} Mpc
Source redshift z	$0.09^{+0.03}_{-0.04}$

Table 2: Basic information of the detected BBH [4]
(a more comprehensive table, Table 5, attached at the end)

As of the interest of this paper, we look at the possible rate of detection inferred from the detection. The full deduction and discussion can be found in LIGO paper [1]. There are some assumptions made when inferring the rate. First, only GW150914 is considered. Second, it is assumed that all BBHs in the universe have the same masses and spins as this event. Third, a false alarm threshold of 1 per 100 years was imposed. Fourth, the BBH rate is assumed to be constant in the commoving frame. An 90% credible range of 2-53 Gpc^{-3} yr^{-1} [1] is reported basing on these assumptions. To get a full conservative range, they incorporated uncertainty about astrophysical origin of all search triggers that could represent BBH signals, assumed BBH rate is constant in both co-moving frame and source-frame time, and take into account assumptions about mass distribution of merging BBH systems. From these, they got an inferred rat
e of 6-400 Gpc^{-3} yr^{-1}. Combining all the considerations, the improved rate is 2-400 Gpc^{-3} yr^{-1} in the co-moving frame [1].

Other implications of this event include the possible stellar BH masses --- up to ~30 $M_\odot$; its localization --- located in the southern hemisphere, etc. A complete discussions of the astrophysical implication of this event can be found in the LIGO paper [8].

1.5 Other Signals obtained

In the Physics Review Letter [4] of the detection, there are 4 events including GW150914 during the same run. The other 3 events are not considered to be official signals as their false alarm probability(FAP) is high, with the second most significant signal having a FAP of 0.02 and false alarm rate(FAR) of 0.43 yr^{-1}, comparing to 2 x 10^{-7} and 4.9 x 10^{-6} yr^{-1} for GW150914 [1]. There are some discussions on the second significant signal in the LIGO rate paper [1], assuming it may be of astrophysical origin.

2. Astrophysical Arguments on Detection Rate of GW150914-like Binary Black Holes

Before the detection, binary black holes were mainly considered to be formed in two types of environments--- in isolated binary systems, or in dense stellar environment. In this section, we discuss the rate of detection calculated from these astrophysical perspectives. We also include the relatively new competitive model concerning BBHs formed from chemically homogeneously binaries. Only models that allow the formation of the BBHs in GW150914 are discussed. Apart from checking the consistency between the theoretical calculation and the inferred rate obtained though the observations on the GW150914 detection, we also look at the underlying assumptions made during the deduction of detection rates.

2.1 Binary Black Holes from Chemically Homogeneous Evolution

A newly proposed model by I. Mandel and S. E. De Mink [2] suggested BBHs can be formed from two chemically homogenously evolving stars. This model starts with the idea that stellar rotation affects the evolution of close massive stars in binary systems as progenitors of double compact mergers. Each massive and rapidly rotating star can trigger mixing, and tides help transport substance between the hydrogen- rich envelope and central burning region. The build-up of internal chemical gradients is prevented as the star is enriched with helium. The two stars evolve chemically homogeneously and become two black holes, which merge in 4-11 Gyr after formation [2].

There are several features that could possibly be used to observationally distinguish this model. First, this model tends to produce nearly equal masses BBH. For $q = m1/m2$, there are no $q < 0.5$ produced in the channel, and 70% of mergers come from sources with $q > 0.75$ [2]. Second, the total mass of the binaries produced is high, around 50-110 $M_{\odot}$ [2]. Third, the BH spins are nearly aligned if the spin directions are conserved during supernovae (i.e. have no spin tilts). This is due to the fact that possible supernova natal kicks are expected to be small comparing to high orbital velocities of the progenitor stars. Forth, most merging BH in this channel occur in relatively low redshift, with $z < 1.5$ [2].

Note that the last characteristic is particularly in contrast with what happens in conventional isolated binary evolution(IBE) scenario. In IBE channel, shrinkage of the orbit during the common envelope phase cause the BBH merger with very short time delay after their formation, where for chemically homogeneous evolution (CHE) channel, mergers have minimal delays of a few Gyr. As a result, IBE channel produces many high-redshift mergers, versus CHE, which has very few mergers beyond $z \sim 1.5$ [2].

The rate of mergers estimation is done by considering a Drake-like equation. The following equation gives the rate of local mergers per unit volume per unit time (equation (2) in the paper[2]):

$$\frac{dN}{dV\,dt} = \frac{dN_{\rm gal}}{dV}\dot{N}_{SF} f_Z f_{\rm mass} f_{\rm sep}$$

To do the estimate on the rates, the following numbers and considerations are adapted. dN_{gal} / dV is number density of galaxies, and a space density of Milky Way equivalent galaxies(MWEGs) of 0.01 Mpc^{-3} [5] is used. N_{SF} is the rate of stars formed per galaxy per unit time, and is set at 2 yr^{-1}. f_z is the fraction of stars formed at metallicities of interest, taken to be 0.1 at metallicity Z <= 0.004. f_{mass} is the fraction of stars formed in binaries in the mass range of interest, assumed to be 10^{-4}. Lastly, f_{sep} is the fraction of binaries in the required range of separations and set at 0.1 [2].

The above estimations gives a rough estimate of around 20 Gpc^{-3} yr^{-1} :

$$\frac{dN}{dt} \sim \frac{0.01}{\mathrm{Mpc}^3} \times \frac{2}{\mathrm{yr}} \times 0.1 \times 10^{-4} \times 0.1 \sim 20\ \mathrm{Gpc}^{-3}\mathrm{yr}^{-1}.$$

More precise and updated numbers can be found in Table 6 [9] in the Appendix section. The full details of the models can be found in paper [9].

The key uncertainties of this scenario lie in the efficiency of the mixing processes in tidally locked binaries and the effects of stellar winds on orbital evolution, which can entirely close off this channel or change the predicted rates by factors of several [2].

2.2 Binary Black holes from Isolated Binaries

Here we follow a series of papers concerning BBH formed from isolated binaries(IB) by four StarTrack evolutionary models--- 1) the standard model (also referred as M1 in Table 4), 2) optimistic common envelope (Optimistic CE, M2) model, 3) delayed supernovae model (Delayed SN), and 4) high BH kicks model (M3). The complete description of the standard model can be found in paper [10]. The latter three models are different versions of the standard model with only the indicated parameter modified, thus the only factor making the rates differ from the standard model.

In the optimistic CE model (M2), Hertzsprung gap stars are allowed to enter and possibly survive the common envelope, forming BBH mergers. This is considered to be an optimistic model as HG stars may not survive the CE phase and merge into a single star instead, or the CE may never develop with HG stars [11]. Other models discussed here assumed that no HG stars lead to formation of the BBH.

In the delayed SN model, the supernova explosion engine is changed with respect to the standard model--- it used a delayed supernova engine as discussed in the paper [10] instead of a Rapid one. The main feature of this model is that it produces compact objects with a continuous mass spectrum, covering the 2-5 $M_\odot$ gap that the standard model missed. Thus the minimal total mass of BBH in this model is ~5 $M_\odot$, where the other models yield a minimal total mass of ~10 $M_\odot$ [10].

In the high BH kicks model, full natal kicks are employed on the BHs. Many BBHs are disrupted in this variation, even the merger rate of massive systems (start with single star with mass > 40 $M_\odot$) is lowered [10].

Model	$\left\langle \mathcal{M}_c{}^{15/6} \right\rangle$ $M_\odot^{15/6}$	$\mathcal{R}(0)$ $\mathrm{Gpc}^{-3}\,\mathrm{yr}^{-1}$	R_D (aLIGO $\rho \geq 8$) yr^{-1}	R_D (3-det network $\rho \geq 10$) yr^{-1}
NS-NS				
Standard	1.1 (1.1)	61 (52)	1.3 (1.1)	3.2 (2.7)
Optimistic CE	1.2 (1.2)	162 (137)	3.9 (3.3)	9.2 (7.7)
Delayed SN	1.4 (1.4)	67 (60)	1.9 (1.7)	4.5 (4.0)
High BH Kicks	1.1 (1.1)	57 (52)	1.2 (1.1)	3.0 (2.7)
BH-NS				
Standard	18 (19)	2.8 (3.0)	1.0 (1.2)	2.4 (2.7)
Optimistic CE	17 (16)	17 (20)	5.7 (6.5)	13.8 (15.4)
Delayed SN	24 (20)	1.0 (2.4)	0.5 (0.9)	1.1 (2.3)
High BH Kicks	19 (13)	0.04 (0.3)	0.01 (0.08)	0.04 (0.2)
BH-BH				
Standard	402 (595)	28 (36)	227 (427)	540 (1017)
Optimistic CE	311 (359)	109 (221)	676 (1585)	1610 (3773)
Delayed SN	829 (814)	14 (24)	232 (394)	552 (938)
High Kick	2159 (3413)	0.5 (0.5)	22 (34)	51 (81)

Table 3: Local merger rates and simply-scaled detection rate predictions [12]

Model	Type	O1 rate [yr^{-1}]	O1: 16 days
M1	All	63.18	2.770
	NS-NS	0.052	0.002
	BH-NS	0.231	0.010
	BH-BH	62.90	2.758
	GW150914	11.95	0.524
M2	All	476.1	20.87
	NS-NS	0.191	0.008
	BH-NS	0.796	0.035
	BH-BH	475.1	20.83
	GW150914	110.0	4.823
M3	All	1.985	0.087
	NS-NS	0.039	0.002
	BH-NS	0.014	0.001
	BH-BH	1.932	0.085
	GW150914	0.270	0.012

Table 4: Expected detection rate and number of detections. M1 = Standard model; M2 = Optimistic CE model; M3 = High BH kicks model. Entries marked with "GW150914" are for the subpopulation of BH-BH mergers with total redshifted mass in the range $M_{tot,z} = 54 – 73\ M_\odot$ [13]

The delayed SN model does not affect the merger rate of any type of compact objects significantly. Also as noted in the paper [13], the standard, optimistic CE and high BH kicks model covered the possible range of merger rate in this scenario, therefore we focus on these three models (M1, M2, M3) when we discuss the merger rate here. However, from Table 4, we can immediately exclude the M2 model (i.e. the optimistic CE model) for GW150914-like BBH as it inferred an unrealistic high detection rate which is way exceeding what was detected in the recent LIGO run. This is not surprising as stars only stay in the HG stage for a very short period of time, therefore as what we stated above, the model itself is an optimistic model that the interested scenario may not even happen.

From Table 3 of the 2015 paper [12], a rate of 0.5-221 $Gpc^{-3}\ yr^{-1}$ [12] are calculated for BBH mergers, which agree to what we have from GW150914. If we further consider the revised detection rate in the newest paper of these model, i.e. Table 4, the standard model(M1) will be a more probable model for GW150914-like BBH mergers from the isolated binaries evolution scenario.

Here we want to include a small discussion on spins, which is considered to be one of the key features of this scenario. Their models of isolated BBH formation favour aligned BH spins, which assume that the progenitor star spins are aligned when the binaries form. If a BBH merger shows strong spin alignment properties, it could distinguish BBHs formed from isolated binaries scenario from the dense stellar evolution scenario, as the latter tends to have significant misalignment [8]. However, if the merger has misaligned spins, then one cannot simply distinguish the two models merely by spin. As was explained in the 2016 paper [13], misaligned massive BBH mergers can be produced if non-aligned initial binary configurations are allowed and binary component spins are prevented from aligning during the mass transfer and CE phases. Examples of unevolved binaries with established misaligned spins can be found in a paper from the BANANA (Binaries Are Not Always Neatly Aligned) project [14]. As reported by LIGO [8], the upper limit (spin <~ 0.7) shows that the GW150914 BBH was not formed with extremal spin. With only the evidence for relatively small magnitudes of BH spin components aligned with the orbital angular momentum, it does not provide constraints on the formation mechanism.

2.3 Binary Black Holes from Dense Stellar Environment (DSE)

Different models concerning BBHs forming in dense stellar clusters were suggested before the detection. There are several types that are considered to be particularly important, including globular clusters(GCs), and nuclear star clusters with or without a massive black hole. In general, BBHs formed in this scenario have higher masses.

The Rodriguez 2016 paper [15] presented the discussion on BBH mergers from globular clusters. They used their cluster Monte Carlo code to create a broad range of GC models with different initial conditions, including masses, metallicities, initial virial radii, temperature-dependent stellar winds for O and S stars, etc. When computing the merger rate, they assumed all GCs to be 12Gyr old [15]. They found that more massive and more compact clusters create more BBHs, and they eject BBHs with high binding energies and smaller semi-major axes, resulting a larger number of BBHs to merge within 12 Gyr [15]. The mechanism is that three body interactions in the cluster lead to a hardening of a binary, and most of the release energy appears in the kinetic energy of the binary. As the hardening proceeds, the binary eventually escapes the cluster.

In their models, the most massive BHs produced lead the first period of mass segregation and drive the collapse of the cluster core. Those BHs then dynamically form BBHs that are first to be ejected from the cluster and merge. The process continued for BH population from most to least massive, and keep ejecting BBHs up to the present day. As a result, the total mass of BBHs mergers decrease with redshift, with a median BBH total mass in the local universe of around $40M_o$ and 50% of sources lies between around 30 M_Θ to 90 M_Θ [15]. The range of BBHs total masses ranged from 20 M_Θ to 160 M_Θ [15]. They also found that these massive BBHs are more likely to form in lower mass GCs as they eject binaries with longer inspiral times and wider separations [15].

The merger rates in this BBHs population are calculated as a function of redshift. A range of 2 Gpc^{-3} yr^{-1} to 20 Gpc^{-3} yr^{-1} results for the local universe, where a merger rate of 2 Gpc^{-3} yr^{-1} is found for sources with total masses 40 M_Θ to 80 M_Θ [15].

In the paper [15], they suggest that there is not always a clear cut-off between BBHs form from isolated binaries and globular cluster. They propose that some BHs formed in the globular cluster may contribute to what later form as BBHs in isolated binary systems. While they found that approximately 1 out of every 7 BBH mergers in local universe will have originated in a globular cluster [15], this fraction increased significantly and will dominate the merger rate if BHs are born with large natal kicks. This is counter-intuitive as it is always assumed that majority of BHs with large natal kicks would be ejected, and only a small fraction can retain and process into BBHs. However, the paper explained their idea by the following reasoning.

Assume that some fraction f_{ret} of BHs born with low kicks and remain gravitationally bound to a GC or a binary star system. For a GC, N f_{ret} of the total N BHs will be retained in the cluster. Assuming some fraction f_{BBH} of these BHs dynamically formed BBHs, then the total number of BBHs produced by the cluster is $N_{BBH} \propto N\, f_{ret}\, f_{BBH}$ [15]. However, each BBH from the isolated binaries must be formed from a binary progenitor, and therefore each binary must survive two natal kicks in the M3 scenario. Then from an initial population of N_{bin} binaries, the number of BBHs produced by the IB field in this scenario is

$N_{BBH} \propto N_{bin} (f_{ret})^2$ [15]. Thus, if the BH natal kicks are inversely proportional to the fraction of retained BHs, then as the kicks increased, the rate from GCs decrease as the magnitude of the kick V_{natal}, and the rates from the IB field decrease as $(V_{natal})^2$ [15].

There are two older papers that discuss the nuclear star cluster case. One of them argues that stellar mass black holes in galactic nuclei with a supermassive black hole create steep density cusps with enough scattering interactions to form a significant number of tight BBH through two-body scattering [16]. The key and distinguishable signature of this evolution is that the BBH formed have significant eccentricities as they enter the LIGO band, with 90% having $e > 0.9$ [16]. From the LIGO paper [8], there are no evidence for eccentricity concerning the orbit of GW150914, although eccentricities $e <\sim 0.1$ would not be detectable [17]. So here we omit this case for the rate discussion on GW150914-like BBHs.

Another model [18], as noted in the beginning of this section, suggests that BBHs can be formed in nuclear clusters without a supermassive BH. In particular, they suggest BBH mergers may occur in the center of small galaxies though three-body dynamics of BHs. However, the resulted single BH masses ranged from 3 $M_\odot$ to 20 $M_\odot$ [18]. Therefore, we also omit the discussion about this model.

In our interest of GW150914-like detection, the globular cluster models seem to be more probable if we are considering the dense stellar evolution path. However, another paper on isolated binary evolution pointed out that the existence of GW150914 indicates that large natal kicks for massive BHs are unlikely [13]. Therefore, as suggested in the paper above concerning globular cluster, only around 15% of merger will originate from the model [18]. Note that this is a rather low number considering the large uncertainties in star evolution models.

2.4: Summary on the Implications from the Three Formation Path

The three mentioned formation path are all possible for GW150914-like mergers. With only one detection, we could not draw a definite conclusion on which of the formation models corresponds to the detection. However, from the discussion of the three formation paths above, the CHE scenario and the IB scenario are more probable for GW150914 over the DSE model.

An interesting idea of studying the origin of the BHs forming BBHs later is proposed as mentioned in the DSE section (Section 2.3) above, which suggested that some BHs in the isolated binaries scenario may have originated in a globular cluster [15]. This idea questioned the assumption that BBHs from DSE and IB are unrelated, and if this is true, the merger rates of the two scenario may not be simply combined.

Although the mass of BHs in GW150914 is a key discovery in the astrophysics field, we noticed that the mass of the system cannot be a distinguishable feature for formation paths, as all three scenarios can produce high mass BHs like GW150914. Spins or spins' alignment will be an important feature, as significantly misaligned spins support the DSE formation path and strongly aligned spins will lean towards the IB formation model, but there is not enough discussion on the spin alignment in the CHE model available for fair comparison.

3. Looking Forward: Future Studies on BBH mergers

Important Aspects to be Considered in Distinguishing Formation Models

As noted in the summary of Section 2, further studies should examine the idea that some BHs in isolated binaries scenario is originated in a globular cluster. Even if this is not a valid argument, the question of whether different scenarios are completely distinct with each other is worth asking, as this affects how we place the constraints on the simulations, and how we compare the merger rates from different models.

While there are a lot of comparisons and discussion on how to distinguish BBHs formed from the IB models and the DSE models, there is as yet no discussion between those two with the relatively new CHE model. For example, while the spins' alignment of the BHs in the BBH system are generally considered to be a key feature to distinguish between IB and DSE model, it is not clear we can distinguish the aligned spins suggested in IB model from that of the CHE model. As we can see in Section 2 of this paper, the CHE model is a competitive model especially for higher masses BBHs. Future studies on the two conventional models should take CHE models into considerations.

Possible EM Signal Counterpart and Future Cooperation with LIGO

Although it is not expected for BBH merger to give out any electromagnetic(EM) signals, observations by the Fermi Gamma-ray Burst Monitor (Fermi GBM) [19] and the followed discussion by Loeb [20] raised the idea that there might be EM counterparts for certain formations of BBH. Fermi GBM reported a EM signal near the time of the GW150914 event a few days after the LIGO announcement [19]. Shortly after the report, Loeb suggested that the events are correlated if GW150914 is originated from two clumps in a dumbbell configuration that formed when the core of a rapidly rotating massive star collapsed [20]. Although now the Fermi GBM detection is generally considered to be a random signal as the other gamma-ray observatory INTEGRAL observed nothing during the same time [21], it facilitated studies on EM counterpart of BBH mergers and how EM observatories can cooperate with LIGO. With more gravitational wave detections in the future, EM counterparts can help to constrain observed quantities, especially the localization of the GW signal. A more detailed study can be found in the Fermi GBM paper concerning the discussion on the EM counterpart of GW150914 [19].

eLISA

One of the key disadvantages of LIGO is that it is a ground-based observatory, which is greatly affected by the movement of the earth and related noises. eLISA, the Laser Interferometer Space Antenna, will have the advantage over LIGO concerning that issue as it is in the space. Although eLISA is sensitive to lower frequency GW signals [22], its detections on signals of merging supermassive black holes and stars/BHs being swallowed by supermassive black holes to understand what happens in star clusters, thus BHs formed particularly in the dense stellar environment. A recent paper also suggests the possibility that eLISA could observe a GW150914-like signal, and notably measure the eccentricity of BBHs as small as $e \sim 0.02$ [23].

4. Conclusions

In this paper, we looked at the three possible formation paths for GW150914-like BBHs mergers. They are the chemically homogenously evolution, isolated binaries scenario, and the dense stellar environment scenario. With the inferred merger rate of 2-400 $Gpc^{-3}\ yr^{-1}$ from the detection of GW150914 [1], these three models predicted consistent merger rates. Although with one single detection, a definite conclusion cannot be drawn on which scenario correspond to GW150914-like signal, we found that the IB scenario and CHE scenario are more probable. Some features are considered to be particularly important to distinguish the three models. Strong spin alignment can possibly distinguish isolated binaries scenario from the dense stellar environment scenario, and with both IB and CHE scenario favour aligned spins, the BBH formed from CHE scenario mostly merge in $z < 1.5$ [2], while that of IB can occur in high red shift. Further studies on comparison between the two conventional models (IB and DES) and CHE model is needed in order to identify features that can better distinguish the three models, and improve the constraints on the spins and redshift of BBHs.

Appendix: Supplementary Graphs and Tables

Table 5: Complete summary of the parameters that characterize GW150914. The spin-aligned EOBNR and precessing IMRPhenom waveform models are described in the paper [4]. The Overall results are computed by averaging the posteriors for the two models [4].

	EOBNR	IMRPhenom	Overall
Detector-frame total mass $M/\mathrm{M}_\odot$	$70.3^{+5.3}_{-4.8}$	$70.7^{+3.8}_{-4.0}$	$70.5^{+4.6\pm0.9}_{-4.5\pm1.0}$
Detector-frame chirp mass $\mathcal{M}/\mathrm{M}_\odot$	$30.2^{+2.5}_{-1.9}$	$30.5^{+1.7}_{-1.8}$	$30.3^{+2.1\pm0.4}_{-1.9\pm0.4}$
Detector-frame primary mass $m_1/\mathrm{M}_\odot$	$39.4^{+5.5}_{-4.9}$	$38.3^{+5.5}_{-3.5}$	$38.8^{+5.6\pm0.9}_{-4.1\pm0.3}$
Detector-frame secondary mass $m_2/\mathrm{M}_\odot$	$30.9^{+4.8}_{-4.4}$	$32.2^{+3.6}_{-5.0}$	$31.6^{+4.2\pm0.1}_{-4.9\pm0.6}$
Detector-frame final mass $M_\mathrm{f}/\mathrm{M}_\odot$	$67.1^{+4.6}_{-4.4}$	$67.4^{+3.4}_{-3.6}$	$67.3^{+4.1\pm0.8}_{-4.0\pm0.9}$
Source-frame total mass $M^\mathrm{source}/\mathrm{M}_\odot$	$65.0^{+5.0}_{-4.4}$	$64.6^{+4.1}_{-3.5}$	$64.8^{+4.6\pm1.0}_{-3.9\pm0.5}$
Source-frame chirp mass $\mathcal{M}^\mathrm{source}/\mathrm{M}_\odot$	$27.9^{+2.3}_{-1.8}$	$27.9^{+1.8}_{-1.6}$	$27.9^{+2.1\pm0.4}_{-1.7\pm0.2}$
Source-frame primary mass $m_1^\mathrm{source}/\mathrm{M}_\odot$	$36.3^{+5.3}_{-4.5}$	$35.1^{+5.2}_{-3.3}$	$35.7^{+5.4\pm1.1}_{-3.8\pm0.0}$
Source-frame secondary mass $m_2^\mathrm{source}/\mathrm{M}_\odot$	$28.6^{+4.4}_{-4.2}$	$29.5^{+3.3}_{-4.5}$	$29.1^{+3.8\pm0.2}_{-4.4\pm0.5}$
Source-fame final mass $M_\mathrm{f}^\mathrm{source}/\mathrm{M}_\odot$	$62.0^{+4.4}_{-4.0}$	$61.6^{+3.7}_{-3.1}$	$61.8^{+4.2\pm0.9}_{-3.5\pm0.4}$
Mass ratio q	$0.79^{+0.18}_{-0.19}$	$0.84^{+0.14}_{-0.21}$	$0.82^{+0.16\pm0.01}_{-0.21\pm0.03}$
Effective inspiral spin parameter χ_eff	$-0.09^{+0.19}_{-0.17}$	$-0.03^{+0.14}_{-0.15}$	$-0.06^{+0.17\pm0.01}_{-0.18\pm0.07}$
Dimensionless primary spin magnitude a_1	$0.32^{+0.45}_{-0.28}$	$0.31^{+0.51}_{-0.27}$	$0.31^{+0.48\pm0.04}_{-0.28\pm0.01}$
Dimensionless secondary spin magnitude a_2	$0.57^{+0.40}_{-0.51}$	$0.39^{+0.50}_{-0.34}$	$0.46^{+0.48\pm0.07}_{-0.42\pm0.01}$
Final spin a_f	$0.67^{+0.06}_{-0.08}$	$0.67^{+0.05}_{-0.05}$	$0.67^{+0.05\pm0.00}_{-0.07\pm0.03}$
Luminosity distance $D_\mathrm{L}/\mathrm{Mpc}$	390^{+170}_{-180}	440^{+140}_{-180}	$410^{+160\pm20}_{-180\pm40}$
Source redshift z	$0.083^{+0.033}_{-0.036}$	$0.093^{+0.028}_{-0.036}$	$0.088^{+0.031\pm0.004}_{-0.038\pm0.009}$
Upper bound on primary spin magnitude a_1	0.65	0.71	0.69 ± 0.05
Upper bound on secondary spin magnitude a_2	0.93	0.81	0.88 ± 0.10
Lower bound on mass ratio q	0.64	0.67	0.65 ± 0.03
Log Bayes factor $\ln \mathcal{B}_{\mathrm{s/n}}$	288.7 ± 0.2	290.1 ± 0.2	—

Table 6: Quantification of the impact of model variations from the chemically homogeneous evolution formation path [9]. R_{detect} is the detection rate at full sensitivity, and N_{detect} is the expected number of detections at the sensitivity of O1 for a 16 day period of double0-coincident observations. Details about the models can be found in paper [9].

ID	Model	R_{detect}(full) (yr^{-1})	N_{detect} (O1) (per 16 days)	$\mathcal{M}_c$ ($\mathrm{M}_\odot$)	m_{tot} ($\mathrm{M}_\odot$)	q	m_1 ($\mathrm{M}_\odot$)	m_2 ($\mathrm{M}_\odot$)	Description
0	`DefaultFull`	470	-	35^{+10}_{-10}	82^{+21}_{-25}	>0.66	44^{+11}_{-15}	36^{+15}_{-10}	Standard, full design sensitivity
0	`DefaultO1`	-	1.8	34^{+11}_{-10}	80^{+24}_{-24}	>0.68	44^{+12}_{-14}	35^{+15}_{-9}	Standard, O1 sensitivity
1	`PoorMixing`	230	0.6	32^{+10}_{-6}	74^{+24}_{-14}	>0.72	41^{+14}_{-11}	34^{+9}_{-7}	Red. Case M window
2.1	`Zmin0.002`	91	0.3	35^{+9}_{-9}	84^{+17}_{-22}	>0.65	47^{+9}_{-14}	35^{+12}_{-9}	Red. metallicity threshold (0.002)
2.2	`Zmin0.008`	540	2.5	35^{+9}_{-10}	80^{+20}_{-24}	>0.68	47^{+8}_{-18}	36^{+14}_{-10}	Inc. metallicity threshold (0.008)
3.1	`ConstA`	1200	1.4	34^{+10}_{-11}	79^{+22}_{-25}	>0.68	42^{+14}_{-14}	35^{+13}_{-10}	Slow winds (fixed sep.)
3.2	`HalvedA`	1000	1.2	34^{+10}_{-11}	78^{+23}_{-25}	>0.69	44^{+10}_{-16}	35^{+12}_{-10}	Slow winds (halving sep.)
4.1	`Mdot2`	0.0	0.0	-	-	-	-	-	Enh. mass loss (doubled)
4.2	`Mdot2ConstA`	620	1.5	26^{+14}_{-12}	59^{+32}_{-27}	>0.55	34^{+15}_{-17}	26^{+19}_{-11}	Enh. mass loss & slow winds
4.3	`Mdot0.2`	1500	1.6	39^{+11}_{-9}	91^{+23}_{-22}	>0.74	50^{+10}_{-14}	42^{+14}_{-9}	Red. mass loss (by factor of 5)
5	`PISN80`	600	2.1	40^{+8}_{-16}	93^{+17}_{-37}	>0.59	51^{+16}_{-19}	37^{+18}_{-11}	Enh. PISN threshold ($80\mathrm{M}_\odot$)
6	`Dex0.5`	1400	10	34^{+10}_{-10}	77^{+24}_{-22}	>0.71	43^{+11}_{-14}	37^{+13}_{-11}	Enh. metallicity spread (0.5 dex)
Combined		0–1500	0–10	14–50	32–114	>0.55	17–67	15–56	Union of 90% ranges
GW150914			1	28^{+2}_{-2}	65^{+5}_{-4}	>0.65	36^{+5}_{-4}	29^{+4}_{-4}	Abbott et al. (2016e)

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